Circuit and System Education

Engineering in general and electrical engineering in particular are evolving disciplines, and hence their educational processes have not stagnated either over the past 90 years. Equally important is the dynamical balance between on the one hand the improved understanding of circuits and systems, and the accumulated CAS knowledge over the past century and on the other hand the different characteristics of the new generations of students with natural exposure to new ICT media, and devices and the students' limited attention span. This tension requires creative processes that incorporate advanced technologies of blended learning, MOOCs, and learning analytics as well as rethinking the educational trajectories and the choice of relevant CAS topics for the new students.

Clearly there is a process of rethinking the CAS education, where we can learn from the past 90 years, and project in the future, in order to prepare the students with CAS skills and insights for their role in society during the coming 40-50 years. This is the context of the CAS Education and Outreach TC of IEEE CAS Society that was set up in 2009.

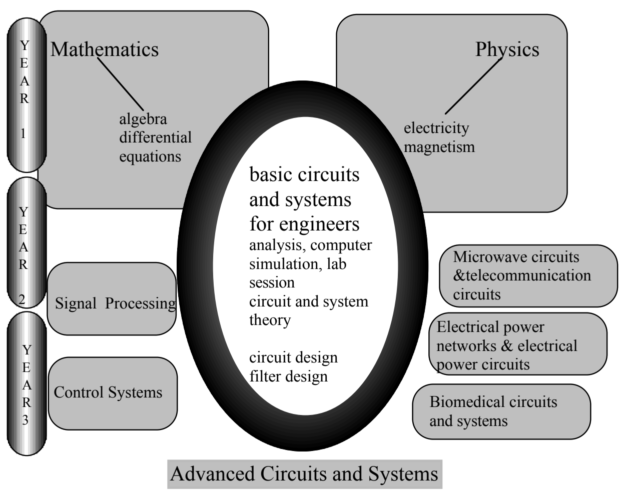
Ernst Guillemin is generally considered [1,2] as the founding father of circuit theory education with a magisterial series of six single-authored books written at MIT. Under the leadership of Vannevar Bush a modernization of the EE curriculum at MIT was launched in the late 1930s and 1940s that is more based on sciences like physics and mathematics than on craftmanship. Guillemin had moved temporarily from MIT to the University of Munich, Germany, for a doctorate in mathematical physics in 1926 with Arnold Sommerfeld. Conversely in 1930-1931, Wilhelm Cauer came from Germany to MIT to work in the team of Bush and Guillemin. In his textbook [3] of 1931 Guillemin introduced new topics like transient and steady-state response, network theory, the Heaviside approach, and Fourier analysis. In the preface he gave a message both for students and teachers that describes the dynamical relationship between research and education and that still resonates today: *"Methods are frequently designated as advanced merely because they are not in current use. To the student the entire field is new; the advanced methods are no exception. If they afford better understanding of the situation involved, then it is good pedagogy to introduce them into an elementary discussion. It is well for the teacher to bear in mind that the methods which are very familiar to him are not necessarily the easiest for the student to grasp."* His continuing work on course revision and development led him [4] to take a particular interest in engineering mathematics with topics like determinants, matrices, vectors (including vector calculus), functions of a complex variable, Fourier and Laplace transformations, and conformal mapping. All these topics appear currently in basic linear algebra and calculus courses in EE worldwide, however with a lesser role of determinants, and more attention on eigenvalues and singular values. Moreover these methods still play a central role in courses of systems and control, circuit analysis, and filter design.

The book [5] entitled Introductory Circuit Theory of 1953 takes a fresh approach in the power and generality of essentially quite simple ideas. It even introduces the concepts of graphs, networks and trees, cut-sets, duality and so on before even mentioning Kirchhoff's laws. The book had a great impact, and for example the graph theory is a standard subject in EE and CS. But the book did not itself enjoy great popularity. In [6] he presented a more systematic and rigorous approach for the relatively new discipline of network synthesis. Several famous CAS researchers like Fano, Desoer, Newcomb, and Anderson and educators from the group of Guillemin continued to write classical textbooks on CAS. In a historical perspective Guillemin has produced a whole genealogy of generations of PhD supervision descendants in the Mathematics Genealogy Project. In fact he had 11 PhD students and up until today a total of 2906 descendants. A landmark textbook by Desoer and Kuh (1969) [7] also strongly influenced the teaching of circuits. Because of the great mathematical care it has proven attractive in classes with students having superior mathematical interest, but for many universities worldwide it turned out to be too theoretical. For a deep historical account of the different textbooks, and the respective choices of topics over the period 1934-1984 there is a nice overview of Van Valkenburg [8]. The invention of the transistor and the IC and their enormous capabilities had a major impact and lead to a growing interest in nonlinear components and circuits in basic circuit education. After Chua joined the EECS department in Berkeley the new version of the textbook [9] was consequently extended with nonlinear components and circuits.

The development of inexpensive computers and computational facilities together with strong circuit simulation programs, like SPICE, and system analysis programs, like MATLAB, offered new opportunities for designers and the education of design. This lead some universities to drop or reduce the basic circuit analysis course in favor of a SPICE initiation, so that the students could quickly move to the more exciting design. But some students started thinking that design is merely a trial and error game with SPICE simulations for some random values of components until they hit upon a useful circuit. Rohrer [10] reacted to this evolution in 1990, and stressed that the introductory circuits course should do serious circuit analysis and not just give an introduction to SPICE and a shallow memorization of methods like Thévenin, without foundation. This argument of depth was further confirmed in the overview of Diniz [11] in 1998. With the growing interest in digital signal processing there was a move [12] to reverse the traditional order in EE education of analog circuits and signal processing first and then digital signal processing DSP. There are several arguments in favor of DSP first and the approach was worked out carefully [12]. The notion of impulse signal as a discrete time signal that is 1 at t=0 and 0 elsewhere and the impulse response in discrete time are much easier to grasp by students than the Dirac impulse and the corresponding continuous time impulse response. Indeed the Dirac impulse signal as a limit of a block wave of unit area for a duration going to zero is a quite unnatural continuous time signal, and the solution of differential equations with Dirac impulses is not simple. Also block diagrams with components like delay elements, scaling element and adders are closer to the tangible world of students. Moreover discrete time systems tie in very nicely with the digital systems and computer systems and the system simulation tools on digital computers. However since our physical world is continuous time, it is not recommended to postpone the continuous time systems and circuits education. So there is a growing consensus that EE education should rather deal with discrete time and continuous time in a carefully designed interlaced way. Then the concepts can be introduced in the realm of discrete or continuous time that is most easy to grasp by the student. It is then the ambiton that the students can build in their mind concepts of circuits and systems that integrate continuous time and discrete time models.

The basic circuits and systems education (see figure 1) has currently in most EE programs a rather central role [13] between the basic sciences like mathematics and physics and subsequent courses of signal processing, control, electrical energy, biomedical circuits and systems, microwave and telecommunication systems. An impressively comprehensive overview of the whole field is given in the handbook [14] edited by W. K. Chen. CAS education is encountering other obstacles. The

IC miniaturization and the virtualization of the systems render CAS devices clearly less visible. Moreover our world is dealing with more complex electrical systems in telecommunication and power distribution. Fortunately the progress in computing facilities allow for the simulation of larger circuits and systems. Hence, in order to touch all physical senses of the students, CAS education should involve more lab oriented courses where students learn to explore, experiment and analyze basic circuits and build and measure these. This is often followed by a more mathematically oriented course on circuit and system analysis. Also over the years one can observe a growing divergence [11, 13] between the research agendas and themes of young professors and the basic circuits and systems courses in EE. This implies that many young professor of EE consider the teaching of a basic circuit and systems course as a real burden that is not enriching their research. This does however not stimulate the quality or the attractivity of basic CAS courses. Tsividis [15], counteracted this evolution at Columbia University quite convincingly by exposing the students at an early stage in their EE education to real circuits and their capabilities. It has also triggered a renewed interest in EE. Moreover methods of direct teaching of systems as advocated by Ayazifar [16] at U.C.Berkeley have lead to strong motivation of students.



The present positioning of the basic circuits and systems education among the neighboring topics.

The evolutions in the last 30 years have not only influenced the basic CAS education but also the more advanced CAS courses with topics related to large circuits and especially VLSI circuits, sensors, computer-aided design, layout and routing problems, and graph theory and optimization strategies, analog circuit design, analog signal processing, biomedical circuits and systems, communication circuits, electrical energy distribution systems, electrical power circuits. Over these 30 years the CAS Society has bestowed excellent educators for their teaching of basic and advanced courses with the CAS education award : Eliahu I. Jury, Adel Sedra, Gabor C. Temes, Bede Liu, Sanjit K. Mitra, Yosiro Oono, Mohammed S. Ghausi, Rudolf Saal, Thomas Kailath, Adel S. Sedra, Lawrence P. Huelsman, George S. Moschytz, Wai-Kai Chen, John Choma Jr., M.N.S. Swamy, Robert W. Newcomb, Leonard T. Bruton, Magdy Bayoumi, Paulo Diniz, Christofer Toumazou, Wayne Wolf, Nirmal Kumar Bose, Josef A. Nossek, Andreas Antoniou, Yannis Tsividis, R. Jacob Baker, Sitthichai Pookaiyaudom, Luiz P. Caloba, Sung-Mo (Steve) Kang. This proves the continued importance of CAS education worldwide. Indeed it is vital that the research progress in CAS should continue to be intensely linked to the CAS educational processes.

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